SEP7'55A

Volume 41 August, 1955 *Number 8*

Lubrication

A Technical Publication Devoted to the Selection and Use of Lubricants

THIS ISSUE

FRETTING
AND FRETTING
CORROSION

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LUBRICATION

A TECHNICAL PUBLICATION DEVOTED TO THE SELECTION AND USE OF LUBRICANTS

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Vol. XLI August, 1955 No. 8

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Fretting and Fretting Corrosion

MUCH attention has been given to this subject since it was treated in the March, 1948 issue[1] of this magazine. For instance, a well-attended ASTM Symposium on Fretting Corrosion was held in 1952.[2,3,4,5,6] This featured an excellent review of the subject by Campbell[2] as well as papers on the manifestations and evaluation of fretting, the effect of lubricants, and a discussion of other ways of minimizing this phenomenon. The present issue of LUBRICATION will deal mainly with new developments in the field.

It is now recognized that fretting is a form of wear[2] caused by two surfaces rubbing together, generally with a reciprocating motion of limited amplitude. Such motion is usually linear, oscillating or vibratory. In the common case of ferrous metals fretting in air, a reddish oxide (αFe_2O_3) is usually formed (so-called "friction oxidation") which acts as a lapping compound. This abrasive material may rapidly wear depressions, as in an antifriction bearing race (so-called "false brinnelling").

Fretting damage leads to fatigue failures,[4,7] galling, jamming of critical clearances with abrasive debris, and other bad effects.[7] Its appearance is at times masked by confusion with ordinary red rust (α or $\gamma Fe_2O_3 \cdot H_2O$) when ferrous parts are considered.

Fretting corrosion is a special case of fretting where one or more of the surfaces, or the wear particles therefrom, react with their environment. On one hand, there is evidence that mechanical wear[2,9] initiates fretting, with chemical action or "corrosion" resulting from the exposure of virgin metal surface to the air when such reactive materials are fretted. On the other hand, a recent fundamental study[10] on fretting corrosion of mild steel indicates that oxidation occurs conjointly with mechanical ploughing in air, through cleaning and activation of the metal surface by the mechanical action.

SCOPE OF FRETTING

Glass, wood, jewels, gold, steel; all these will eventually fret if they are forcibly rubbed together with slip of sufficient amplitude, but within a limited area of contact. Aluminum and stainless steel are very susceptible to fretting corrosion. This is explained both by the formation of hard abrasive oxides (Al_2O_3, Cr_2O_3) as debris, and by greater rates of oxygen adsorption of these metals.[10]

As mentioned previously, the fretting corrosion of steel parts occurs widely. This occurrence may be broken down into two main classes, based upon the intended function of the parts in question.[2]

Class One is where the parts are not designed to move, such as shrink fits, press fits, bolted flanges and keyed gears.

Class Two includes bearings undergoing an

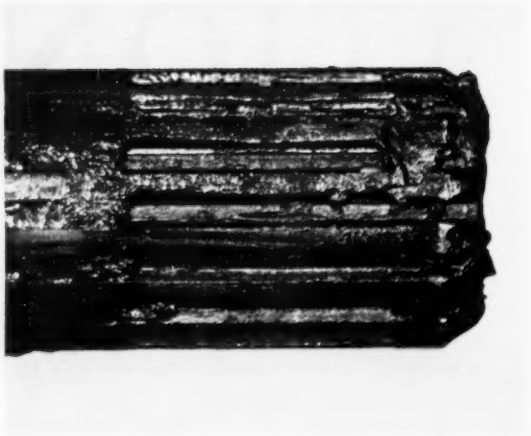


Figure 1 — Fretted spline from test machine rear axle showing typical "red mud" debris of fretting corrosion.

oscillatory motion, flexible couplings, reciprocating cams, etc.

Antifriction bearings span both classifications; for example, consider automotive front wheel bearings. Class One fretting occurs often in service on the face of the outer cup where it is pressed into the housing. In this case, it is not supposed to move. However, under heavy duty service, the cup finally does show relative slip or "creep" and typical fretting may occur. Movement between the bore surface and the shaft may also cause Class One fretting.

A classic example of Class Two occurred when automobiles were shipped extensively in freight cars and the vibration of the carrier caused the automotive wheel bearing balls or rollers to vibrate and/or oscillate in movement of small amplitude, seriously damaging the races.

Much of the confusion surrounding the alleviation of fretting has been caused by the fact that steps taken to correct Class One fretting may actually increase Class Two fretting. Increasing the load is a case in point. This aspect is discussed further on page 93.

Regarding the palliative effect of lubrication, the definition of "lubricant" may be extremely broad — the main objective is to get and keep a third non-abrasive substance between the rubbing surfaces. That this has been considered for some time may be seen in the following quotation* from Leonardo da Vinci (1452-1519); "All things and everything whatsoever, however thin it may be, which is interposed in the middle between objects that rub together lighten the difficulty of this friction."

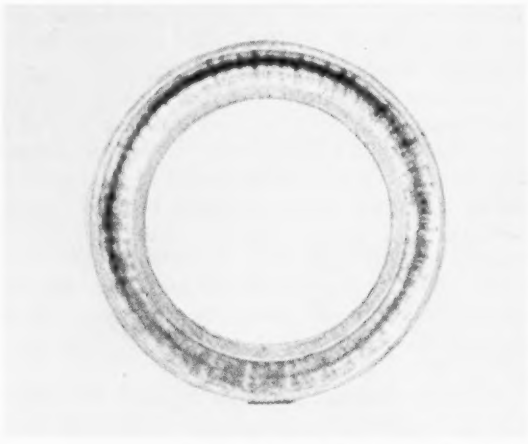
* Heading for Chapter VII of "The Friction and Lubrication of Solids," F. P. Bowden and D. Tabor, Oxford University Press 1950.

DETECTION OF FRETTING CORROSION

As mentioned previously, the great majority of fretting occurrences which result in field complaints are concerned with the rubbing of steel on steel. Fretting corrosion is usually first suspected by finding the familiar "red mud" of hematite (αFe_2O_3). However, the proof that certain damage was caused by fretting is greatly complicated by the fact that ordinary rust is often red. Black iron oxides such as FeO or Fe_3O_4 may also be produced during fretting.

Fortunately, rust can be identified in the laboratory by X-ray diffraction and consists essentially of either red or black iron oxides combined with one molecule of water (red $Fe_2O_3 \cdot H_2O$ or black $Fe_3O_4 \cdot H_2O$). However, the oxides from fretting may also combine with water if exposed to high relative humidity (above 50 per cent) for any length of time; for instance hematite (αFe_2O_3) takes on a molecule of water and becomes a form of rust ($\alpha Fe_2O_3 \cdot H_2O$). Conversely, if the analyst finds the debris to consist essentially of non-hydrated iron oxides, there is a high probability that fretting corrosion (or ordinary wear) has occurred. Even here, though, it must be assumed that these oxides have not been heated above 212°F., either during or after formation. Such heating would dehydrate ordinary rust, changing $\alpha Fe_2O_3 \cdot H_2O$ back to hematite.

The lubrication engineer can contribute greatly to the solution of the above problems. Detailed case histories from the field are invaluable in helping the laboratory decide whether rusting or fretting corrosion has occurred.



Courtesy of The Fafnir Bearing Company

Figure 2 — This fretted aircraft propeller thrust bearing race illustrates the brown stain which fretting corrosion sometimes produces.

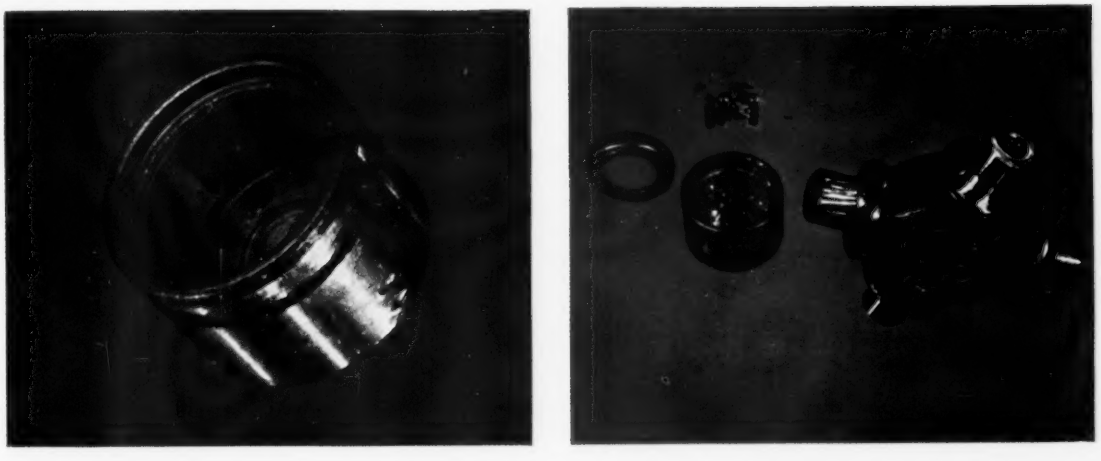


Figure 3 — Extreme case of fretting corrosion damage to the needle bearings of an automotive universal joint. The enlarged photograph (at left) of the needle retaining cup shows the damaged outer race.

MECHANISM OF FRETTING

The general phenomenon of fretting is not dependent upon chemical attack. Fully oxidized materials such as ruby or glass will fret when rubbed together under suitable conditions.[9] Also some fretting of base metals such as steel will occur even if oxygen is excluded; therefore, mechanical wear appears to be the primary factor in fretting.[2]

Not all vibration will produce fretting; its amplitude must be sufficient to cause relative slip between the surfaces.[2] Conversely a point is reached where increased amplitude of oscillation may mitigate fretting by breaking down dams of debris and dragging in fresh lubricant as in the case of grease-lubricated antifriction bearings.[5]

The term "fretting corrosion" was first coined by the English physicist Tomlinson[24] to describe the damage caused by reciprocating motion. He also found that red oxide may accompany uni-directional rubbing.[24,25] Later investigators have also reported that motion in one direction produces the same oxide debris as fretting. For instance, simply drawing a steel ball in one direction over a glass plate will leave a trail of iron oxides.[9] A very recent case has been reported where ball bearings rotating at 8 r.p.m., accompanied by considerable vibration, failed because of fretting corrosion.[11] These unusual cases may possibly be better identified by Campbell's term "wear corrosion"[2] as pictured in Figure 4.

The contributions of Godfrey,[9] Feng and Rightmire[12] and Uhlig et al[10] appear particularly significant in explaining the mechanism of fretting and fretting corrosion.

Godfrey's microscopoic observations published in 1950 present classically simple experiments to elucidate the mechanism of comprehensive fretting. He concludes that fretting is caused by the removal of "finely divided and apparently virgin material due to inherent adhesive forces, and that its primary action is independent of vibratory motion or high sliding speeds."

Materials other than metal-to-metal combinations were fretted by Godfrey, including fully oxidized minerals such as quartz and mica, and the noble metal platinum. Finding that these materials also showed fretting is proof of the primary mechanical nature of this phenomenon.

A typical experiment of Godfrey was that of vibrating a chrome-alloyed steel ball against a glass

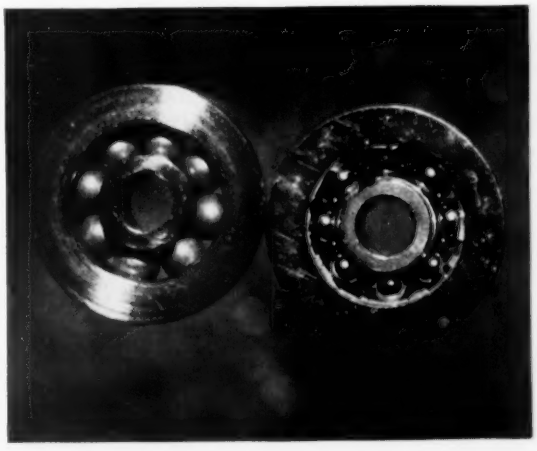


Figure 4 — Example of "wear corrosion." Photo at left represents improperly lubricated aircraft instrument bearing after 300 hours of uni-directional operation. Balls evenly coated with reddish iron oxide (considerable vibration also present). Photo at right shows no trace of corrosion of properly lubricated bearing after 1700-hour operation.

(Originally published in ASTM Symposium Article[2] by W. E. Campbell, describing examples furnished by Lear Inc.)

Figure 5 — Mechanism of wear. (Left) Roughening of the interface of contacting high spots producing a mechanical interlocking effect. (Right) Formation of a loose wear particle.

(Reprinted from article "The Mechanism of Fretting" by I. M. Feng and B. G. Rightmire, Lubrication Engineering, Vol. 9, P. 134.)

specimen plate and observing what happened under the microscope. In this case (with clean surfaces) fretting becomes evident as a small black spot on the ball within one-fourth second. A brown, sticky, semi-fluid oxide is then generated within the contact area, and finally a rust-colored, fine, dry oxide is also formed that accumulates just outside the rubbing area. As the lower oxides of iron (FeO and Fe_3O_4) are usually black whereas ferric oxide (αFe_2O_3) is usually red, the above color changes indicate a progressive oxidation of the abraded-off iron.

The mechanism of metallic fretting proposed by *Feng and Rightmire* in 1953 further substantiates the theory that mechanical wear initiates fretting of metals. Their explanation is based on Feng's theory for the mechanism of metallic wear[13] which postulates that plastic deformation will cause the real points of contact of two metallic surfaces to interlock on a microscopic scale.

The tangential force necessary to move such surfaces relative to each other "will shear off the peak of one of the pair of high spots, instead of separating the contacting high spots along their original interface. The small piece of metal sheared from one high spot becomes a loose wear particle (as shown in Figure 5) if there is nothing to keep it adhering to the other high spot." This happens because strain hardening and interlocking strengthen the area of the interface, causing breaking out to occur in a weaker section of the high spot at a certain distance from the interface. Adherence of the particle to the other high spot will occur, according to Feng, if the heat liberated by the breaking-out action is sufficient to cause welding, or if a strong enough adhesive force exists between the particle and the opposing peak. This explains metal transfer.

The mechanism proposed by Feng and Rightmire is of value in explaining the mechanical component of the fretting of metals; it does not explain, however, how amorphous non-metals fret. In the latter case, plastic deformation would not form the interlocking interface shown for metallic surfaces which show slippage of the crystal planes under compressive stress.

In a uni-directional bearing, or where a wide-amplitude reciprocating motion exists, the loose wear particles easily escape. However, under the limited amplitude reciprocating motion characteristic of fretting, the particles are trapped and accumulate in the "valleys" among the contacting surface asperities. In the usual environment, ferrous particles of this type oxidize mainly to αFe_2O_3, thereby increasing in volume and hardness, forming an abrasive material which produces the typical fretting damage.

Uhlig[10] has developed a theory of fretting corrosion which postulates combined chemical and mechanical action, based on fretting experiments conducted by his co-workers[10] with unlubricated mild steel specimens. Uhlig has summarized his proposed mechanism as follows:

"An asperity rubbing on a metal surface is considered to produce a track of clean metal which immediately oxidizes, or upon which gas rapidly adsorbs. The next asperity wipes off the oxide or initiates reaction of metal with adsorbed gas to form oxide. This is the so-called chemical factor of fretting. In addition, asperities dig below the surface to cause a certain amount of wear by welding or shearing action in which metal particles are dislodged. This is the mechanical factor of fretting."

Uhlig states that the chemical factor of fretting corrosion may cause 6 to 78 per cent of the damage; a physical ploughing causes the remainder of the damage.

Uhlig's theory explains or is consistent with the following experimental findings of his co-workers. These data either are not accounted for by other proposed mechanisms or represent new contributions to the field. The theory is also consistent with other well-established manifestations of fretting.[10]

Figure 6 — Small tapered roller bearing from thrust-loaded test rig: Fretting corrosion was so intense that bearing "froze" and sheared off shaft.

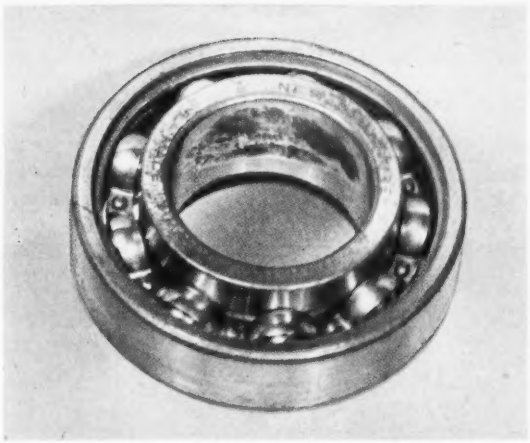


Figure 7 — Dark greyish stain on bore surface of this cleaned-up ball bearing is attributed to fretting corrosion induced by "creeping" on the shaft.

Greater Damage Occurs at Low Frequencies for a Given Number of Cycles Than at High Frequencies

It was found that the weight loss of contacting steel specimens rubbed in air *decreases* with increasing frequency; the loss at 2000 cycles per minute was 1/3 of that at 56 cycles per minute. This is an unexpected occurrence. Uhlig explains this happening as proof of the chemical nature of the greater part of fretting corrosion; it takes *time* for a chemical reaction to occur. When the parts are moving at a fast rate relative to one another, the cleaned surface does not have time to oxidize and the reduced weight loss is due mainly to the physical or ploughing factor.

The frequency effect disappears when the test specimens are run in nitrogen. This is successfully predicted by Uhlig's theory, as the chemical factor of fretting no longer exists in an inert environment. However, the mechanical factor continues to operate in nitrogen to produce a black powdered debris of metallic iron.

Greater Damage Occurs Below Room Temperature Than Above Room Temperature

These data are a refutation of earlier ideas[1] that fretting corrosion was a high temperature oxidation phenomenon initiated by frictional heat. Uhlig points out that metal is less ductile at low temperatures and, therefore, more subject to mechanical attrition. Also it is possible that the rate of adsorption of oxygen on the metal surfaces is greater at low temperature which may more than counterbalance the usual increase of oxidation with increase in temperature. More data are needed along these lines to explain this aspect fully.

In addition, high temperature oxidation of steel produces mostly mill-scale (Fe_3O_4); none of this was found in Uhlig's work, the debris being predominantly αFe_2O_3. Also less damage was observed at high frequency conditions where the highest interface temperatures exist.

Basis the above findings, Uhlig has developed a quantitative expression[10] for fretting corrosion which is as follows:

$$W_{(\text{total})} = \left(k_0 L^{1/2} - k_1 L\right)\frac{C}{f} + k_2 l LC$$

"where W is the specimen weight loss, L is the load, C is the number of cycles, f is the frequency l is the slip, and k_0, k_1, and k_2 are constants. The first two terms represent the chemical factor of fretting corrosion and the third term is the mechanical factor. Accordingly, the equation predicts that fretting corrosion weight loss is a hyperbolic function of frequency, is parabolic with load, and is linear with number of cycles or magnitude of slip. Furthermore, the terms concerned with a frequency effect disappear when the chemical factor is suppressed, as is observed when fretting tests are conducted in nitrogen. These conclusions are confirmed by the presently reported data. In addition, the calculated reaction rate constant for oxidation of a freshly formed iron surface obtained from fretting data is reasonable and falls between two independently observed values."

EFFECT OF LUBRICATION ON FRETTING

Oils and Greases

The worth of conventional lubricants in minimizing fretting and fretting corrosion has been given considerable study in recent years.[2,5,15,16] An outstanding finding has been that the feedability of a grease lubricant is of overriding importance.[15,5] This follows the pioneer work of Almen[7] who

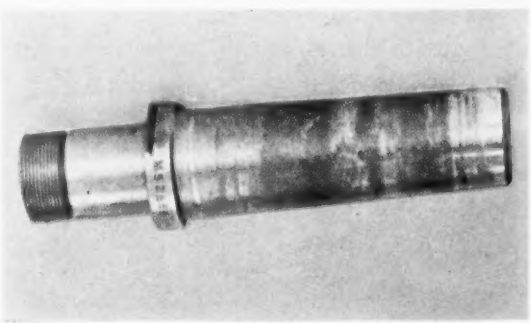


Figure 8 — Fretting corrosion stains produced on galled arbor from bearing test machine. Cantilever loading of test bearing (bearing seat just to left of shoulder) caused flexing of tapered portion of arbor in tapered housing, resulting in relative slip.

TABLE I

Effect of Lubricant Grade (Consistency) on Fretting Corrosion[1]

(550 lb. thrust load; 12° oscillation; 1725 r.p.m. motor speed; 5,175,000 cycles)

Grease	Type Soap	Type Oily Component	ASTM Worked Penetration (60 strokes)	NLGI Grade	Average Weight Loss Per Bearing, Mg.	Standard Deviation $\pm \sigma$
A[2]	Li	Low vis. diester	273	2	500	42
A-1	Li	Low vis. diester	330	1	1.4	0.8
A-2	Li	Low vis. diester	374	0	3.4	1.2
B[3]	Li	Low vis. diester	280	2	450	158
B-1	Li	Low vis. diester	313*	1	49	68
B-2	Li	Low vis. diester	326*	1	0.5	0.3

[1]Determined with Fafnir Ball Thrust Bearing Friction Oxidation Tester.
[2]Heated and stirred prior to testing to bring in line with processing of the other greases.
[3]Same as Grease A, but of a different batch.
*Though both B-1 and B-2 are No. 1 grades, B-2 has a lower soap content.

found that low viscosity oils minimized fretting corrosion to a greater extent than oils of higher viscosities. Thus, submerging a bearing in oil, or using a semi-fluid or shear-susceptible grease is the best general practice if suitable sealing can be accomplished.

If a grease does not feed adequately, fretting corrosion is promoted; simply adding materials[5,16,15] such as zinc oxide, molybdenum disulfide, graphite, tricresyl phosphate or extreme pressure agents to a stiff grease does not help.

Tables I and II, present data[5,16] which show respectively the effect of grease consistency, and of additives, on fretting corrosion. It will be noted that going from an NLGI 2 to a 1 grade by cutting back with an oily component almost eliminates the extensive fretting found with the No. 2 grade. On the other hand, the various materials added to this shear-resistant No. 2 grade lithium soap grease effected no improvement in the high level of fretting shown in the Fafnir-type tester,[1,5] which utilizes unshielded thrust bearings (a very severe condition) as test pieces.

Table III presents test results[5,16] on NLGI 2 grade greases which show that initial NLGI grade per se may not define the feedability and antifretting qualities of a grease. The working or shearing action given to a grease in an antifriction bearing is usually much more intense than the sixty strokes of the ASTM Worker imposed in running the test for Worked Penetration. Greases G and H are very shear resistant; they are not significantly affected even by 100,000 strokes in the ASTM Worker; these greases allow heavy fretting corrosion damage. Greases K, L and M, however, are shear susceptible: they show a large amount of softening after 100,000 Worker strokes and also drastically reduce fretting corrosion as compared to G and H. Grease N, a sodium soap, shear-susceptible grease softens the most and substantially elim-

TABLE II

Effect of Additives on Fretting Corrosion[1]

(550 lb. thrust load; 12° oscillation; 1725 r.p.m. motor speed; 5,175,000 cycles)

Grease	NLGI Grade	Type	Average Bearing Weight Loss, Mg.	Standard Deviation $\pm \sigma$
G	2	Li-Shear Resistant	467	57
G + 3% MoS_2			504	71
G + 3% ZnO			524	38
G + 5% Gallium			547	51
G + 2% TCP*			489	154
G + 5% TCP*			474	23
P	2	Li-Shear Resistant	450	66

[1]Determined with Fafnir Ball Thrust Bearing Friction Oxidation Tester.
*Tricresyl phosphate.

TABLE III

Effect of Lubricant Shear Stability on Fretting Corrosion[1]

(550 lb. thrust load; 12° oscillation; 1725 r.p.m. motor speed; 5,175,000 cycles)

Grease	NLGI Grade	Type	ASTM Penetration[2]	Worked Penetration 100,000 Strokes	Average Bearing Weight Loss, Mg.	Standard Deviation $\pm \sigma$
G	2	Li—Low vis. diester oil—shear resistant	294	283	467	57
H	2	Li—Low vis. mineral oil—shear resistant	276	291	284	37
K	2	Li—Low vis. mineral oil—shear susceptible	289	380	7.1	1.3
L	2	Li—Low vis. diester oil—shear susceptible	286	342	4.6	2.0
M	2	Li—Low vis. diester oil—shear susceptible	277	344	2.3	0.6
N	2	Na—Low vis. mineral oil—shear susceptible	307	400+	1.5	1.3

(1)Determined with Fafnir Ball Thrust Bearing Friction Oxidation Tester.
(2)Sixty strokes.

inates fretting. Yet, all of these products were of NLGI 2 grade to start with.

Table IV gives further data to indicate that the metallic constituent of the soap base, per se, is unimportant in minimizing fretting corrosion. Four, sodium-calcium soap greases reduced fretting to the low-to-very-low range (Grease C, of 2½ NLGI grade, is believed to feed an oily phase, as it is both fairly stiff and fairly shear resistant). Also, two sets of calcium soap greases allowed low-to-negligible fretting depending on their degree of shear susceptibility and of their initial softness. Evidently these soap bases are equally effective with lithium soap in minimizing fretting if the primary criterion of feedability, which does not depend on soap base, is satisfied.

The use of the mineral additive MoS_2 in a very soft (O-grade) grease[5] showed a slight (statistically significant) decrease in fretting corrosion using the Fafnir-type Thrust Bearing Tester, whereas ZnO was ineffective under similar conditions. However, the wear level was so low in these tests that the differences found are of little practical significance. The excellent feedability of the O-grade grease was the great factor in reducing fretting corrosion.

A very recent paper by Godfrey[22] indicates some improvement in reduction of wear spot area for 5 per cent triethyl phosphoro thioate, and for 5 per cent stearic acid in mineral oil as compared to the base oil (steel ball vibrated on steel flat at 30 per cent relative humidity and 75°F). In this paper a distinction is made between the early "lubricated" state, and the later "unlubricated" state in which fretting corrosion increases sharply. In the latter state, dams of debris are thought to seal off the real areas of contact from the lubricant, and rate of wear in this state is indicated to be dependent upon the relative humidity, reaching a peak near 30 per cent RH.

Feng and Rightmire[12] point out that misleading results may be obtained as to the effect of a lubricant in minimizing fretting in two different applications unless the loads are comparable. For instance, the imposed load may be insufficient in one case to cause plastic deformation of the interface to the point where the roughness so produced breaks through the lubricant film. In the second case,

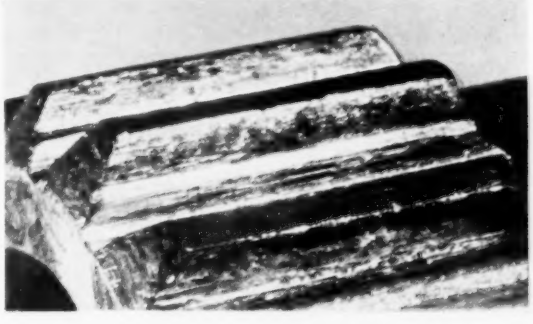


Figure 9 — This supercharger drive spline shows both fretting corrosion stains and extensive metal removal which has worn steps in the teeth.

Figure 10 — These ball bearing raceways show "false brinell" marks from fretting corrosion. They are from an automotive wheel bearing exposed to vibration during shipment of the car.

a greater load may have exceeded this critical value such that the lubricant which minimized fretting in the first place does not now do so. However, it should be mentioned that in the case of antifriction bearings, fretting corrosion may be intensified if the load is so low that skidding of the rolling elements occurs.

More recent work has been done on helicopter rotor-head bearings by the coordinating Research Council in cooperation with the U. S. Air Force. These tests are further described on page 95.

Bonded Films and Sacrificial Coatings

It has been found by Godfrey and Bisson[17] that baked-on films of molybdenum disulfide resin are effective in delaying the inception of fretting corrosion until the bonded film is worn away. This indicates why simply incorporating a mineral additive such as MoS_2 into a grease or oil carrier is usually ineffective; the additive may not get to the zone of action. (See Table II.) The authors studied various ways of applying MoS_2, and have summarized their results as follows:

1. A coating of dry MoS_2 bonded to steel (by rubbing a mixture of MoS_2 and syrup into intimate control with the clean hot metal) proved most effective by delaying the start of fretting corrosion to 28,000,000 cycles for steel balls against glass flats and approximately 10,000,000 cycles for steel flats against steel flats. Under the same conditions, clean uncoated steel specimens showed immediate (less than 100 cycles) fretting corrosion.

2. Dry MoS_2 and mixtures of MoS_2 with various carriers (water and aerosol, light oil, or heavy grease) appreciably delayed fretting corrosion (to as much as 216,000 cycles for the mixture of MoS_2 and heavy grease); however, microscopic observation revealed that MoS_2 may have been ineffective at the contact area. In the mixtures, it is possible that the carrier alone was responsible for the beneficial action.

3. Observations indicated that the effectiveness of any fretting-corrosion inhibitor is dependent on its ability to prevent metallic adhesion continuously.

Sacrificial films of such materials as lead, indium, and phosphate coatings are somewhat effective in preventing fretting. The general subject of solid or dry lubricants has been well reviewed by Campbell.[18]

TABLE IV

Effect of Lubricant Composition and Grade (Consistency) on Fretting Corrosion[1]

(550 lb. thrust load; 12° oscillation; 1725 r.p.m. motor speed; 5,175,000 cycles)

Grease	NLGI Grade	Type	Average Weight Loss Per Bearing, Mg.	Standard Deviation $\pm \sigma$
C	2½	Na-Ca—Fairly shear resistant	14.5	1.6
D-1	2	Na-Ca—Fairly shear resistant	5.3	1.9
D-2	1	Na-Ca—Fairly shear resistant	5.7	1.5
D-3	0	Na-Ca—Fairly shear resistant	2.8	2.5
E-1	2	Ca—Fairly shear resistant	12.0	4.9
E-2	1	Ca—Fairly shear resistant	4.1	3.3
E-3	0	Ca—Fairly shear resistant	0.9	1.0
F-1	2	Ca—Shear susceptible	1.5	0.4
F-2	1	Ca—Shear susceptible	0.8	0.9
F-3	0	Ca—Shear susceptible	0.2	0.4

[1]Determined with Fafnir Ball Thrust Bearing Friction Oxidation Tester.

Courtesy of Sikorsky Aircraft Division of United Aircraft Corp.

Figure 11 — Sikorsky Universal Fretting Corrosion Antifriction Bearing Tester (SKP-1721-1).

OTHER FACTORS WHICH INFLUENCE FRETTING

Load[2,16]

Directly opposed opinions exist regarding the effect of load on fretting. The probable explanation is that the amplitude of vibration and the type of mechanism must be considered in each case. For instance, in fitted parts which are not supposed to show relative movement, a practicable increase in load may suppress vibration and prevent any relative slip from taking place, thus eliminating fretting. However, in the case of an antifriction bearing which is designed to oscillate a limited number of degrees, increase in load may increase fretting because the greater areas of contact produced under load cause more slip as the rolling elements go through the load zone.

Surface Finish and Closeness of Fit[2,19,16]

Both smooth finishes and rough finishes are claimed to minimize fretting. The bulk of the evidence, however, points to the superiority of a rough surface over a smooth surface when a lubricant is used. It has been shown by Rahm and Wurster[19] that vapor blasting the raceways of ball bearings will reduce weight loss due to fretting corrosion — the lubricant is retained in the tiny pockets of the rubbing surfaces. The process of roughening, however, should not be carried to the point of producing a loose fit. In the case of needle bearings,[19] for instance, it has been shown that using a tighter fit eliminates "jiggling" and skewing of the needles and thus decreases fretting corrosion.

Table V is taken from Rahm and Wurster's paper[19]; these results are based on a large number of replicate runs per test. The determinations were made on a modified Fafnir-type thrust bearing tester. The data indicate that the three lubricants tested (best of a number evaluated) rate as follows in their ability to minimize* fretting weight loss: (1) AN-O-8 oil (2) AN-G-25 grease (3) AN-G-15 grease. This holds for both commercial and vapor-blasted finishes; however, the latter finish reduced the level of fretting damage for both greases. Vapor blasting did not further reduce fretting from the negligible weight loss (approximately one milligram) obtained for AN-O-8 oil using the commercial finish. This confirms again that feedability of the lubricant is the primary factor in reducing fretting.

Hardness and Materials

Only meager quantitative information[2] exists on the effects of hardness in minimizing wear under conditions of true fretting. However, it appears that increased hardness is associated with lower susceptibility to attack, as with normal wear. This does not hold true when stainless steel is one of the materials.[3]

Table VI rates various materials and types of surface on their ability to resist fretting corrosion.[20] McDowell[3] also has rated a number of different material combinations in this regard.

Fatigue

The following concluding section from Horger's ASTM Symposium paper[1] well summarizes recent findings and thinking on this aspect.

The fatigue aspects of fretting are somewhat analogous to corrosion fatigue. In both cases:

1. Cracks initiate at very low stresses.
2. The allowable stress, to prevent cracks initiat-

*It will be noted that all weight losses are in the low range of 6.5 to 1.2 milligrams.

TABLE V

*Average Weight or Wear Loss of Bearings**

Comparison of Lubricant and Finish Effectivity

No. of Tests	Type of Finish	Type of Lubricant	Average Weight or Wear Loss, grams	Weight or Wear Loss Differential, grams	Decrease in Wear Due to Lube.	Decrease in Wear Due to Finish
25	Commercial	AN-G-25	.0039	.0026	40%	—
25	Commercial	AN-G-15	.0065			
25	Commercial	AN-G-25	.0039	.0027	69%	—
24	Commercial	AN-O-8 (oil)	.0012			
25	Commercial	AN-G-15	.0065	.0053	80%	—
24	Commercial	AN-O-8 (oil)	.0012			
25	Commercial	AN-G-25	.0039	.0011	—	28%
22	Vapor Blast	AN-G-25	.0028			
25	Commercial	AN-G-15	.0065	.0017	—	26%
27	Vapor Blast	AN-G-15	.0048			
24	Commercial	AN-O-8 (oil)	.0012	.0000	—	0
25	Vapor Blast	AN-O-8 (oil)	.0012			
22	Vapor Blast	AN-G-25	.0028	.0020	42%	—
27	Vapor Blast	AN-G-15	.0048			
22	Vapor Blast	AN-G-25	.0028	.0016	57%	—
24	Vapor Blast	AN-O-8 (oil)	.0012			
27	Vapor Blast	AN-G-15	.0048	.0036	75%	—
24	Vapor Blast	AN-O-8 (oil)	.0012			

*2000-lb. static load; 5° total oscillation; 5,000,000 cycles. (Taken from Rahm and Wurster's paper.[19])

ing, appears to be a function of time or number of stress cycles.

3. If the environment producing fretting or corrosion is removed, once the crack has initiated after a large number of cycles of low stress values, then such cracks will show little, if any, propagation at the same stress required to start the crack.

4. Relatively higher stresses are required to propagate these cracks to complete failure.

The above characteristics may be compared with the usual conception that the same stress which initiates a crack will also propagate it to failure, provided no special environment is present.

An improvement may be made in the resistance to crack initiation, but the increase is somewhat limited. Both shape and favorable residual stresses offer the best means for improvement. The designer will find it almost impossible to prevent cracks initiating when indefinite life is expected. This is confirmed by some of the low allowable stress values reported here[4] for even a limited life of 85 million stress reversals.

Much improvement may be made in greatly retarding the propagation of fatigue cracks initiated by fretting. The best means of doing this are having favorable residual stresses in the shaft surface; shape is also important but gives much less improvement. The use of various engineering steels and commercial heat treatments has been very disappointing from the standpoint of improving the resistance to fatigue crack initiation and propagation.

A real problem still exists in finding means for preventing fatigue crack initiation at such low stresses. Some research is being directed toward this end.

Amplitude of Vibration or Oscillation[2,5,8,10]

In general, fretting tends to increase with amplitude of slip as the area of the rubbed zone is increased. For lubricated antifriction bearings, however, this is true only to the point where fresh lubricant is dragged in by the rolling elements. For instance, weight loss on the Fafnir-type Thrust-Bearing Tester specimens increases with amplitude

up to 12 degrees.[21] However, it is well known that increasing the oscillation of antifriction bearings to 90 degrees or more will decrease fretting corrosion by pulling in sufficient lubricant. Dams of fretted debris become broken down by the longer travel, promoting ingress of lubricant.

Coefficient of Friction

In closely fitted parts not designed to move, it is possible to prevent slip by raising the coefficient of friction, particularly in those cases where the amplitude of slip is low. However, in the case of lubricated antifriction bearings designed to oscillate, a low coefficient of friction is desirable.

Effect of Ambient Temperature

Apparently, high surface temperatures are not a prerequisite of fretting, as glass-on-steel fretting corrosion in air may quickly be obtained under very slow transverse motion (0.002 inch per second) where the occurrence of "hot spots" is very unlikely.[9] While FeO, a high temperature oxide, has been reported in debris from the fretting of steel in air by Dies,[26] there is considerable evidence that fretting can proceed without the necessity of high temperature oxidation. (See page 89 on discussion of Uhlig's theory.)

Effect of Humidity

Several investigators[10,14,22] have studied the effect of relative humidity (RH) in recent years, and find that it influences the amount of metal removed. Wright[14] finds greatest wear at 0 per cent RH but more at 100 per cent than at 50 per cent; Uhlig et al[10] find wear to decrease linearly with increasing humidity, and Godfrey[22] finds a maximum of wear at 30 per cent RH.

The consensus of these studies indicates a definite effect of humidity on fretting corrosion, and may explain why quantitative measurements made at different times with humidity uncontrolled are different. Fretting may become worse in a field application if a very dry period occurs, or increase in the winter as compared to more humid summer.[10]

CRC* Cooperative Experimental Work[23,5,20,16,2]

The CRC Airframe Lubricants Group set up laboratory and service evaluation panels on the subject of fretting corrosion in 1950, at the request of the U. S. Air Force. Fretting corrosion has been particularly serious in helicopter rotor-head bearings, but difficulties have been lessened by application of purging relubrication techniques.

The Laboratory Study Panel has essentially completed Phase I of its work, which was the development of a Tentative Research Technique for Measuring the Effect of Lubricating Grease Characteristics on the Minimizing of Fretting Corrosion in Unshielded Thrust-Loaded Ball Bearings (CRC Designation L-36) based on the ball-thrust-bearing tester originally designed by the Fafnir Bearing Company.[1,5,21,16]

The greases tested by the Laboratory Panel were also tested in full-scale helicopter rotor-head tests[21] by the Service Evaluation Panel in cooperation with Wright Air Development Center. Correlation was obtained with the ball-thrust bearing of the rotor head, but not with radially loaded antifriction bearings of this equipment.

This work has indicated that greases meeting Military Specifications for Automotive and Artillery Grease (MIL-G-10924), and General Purpose Aircraft Grease (MIL-L-7711), allow less fretting corrosion than harder, more viscous greases. This is in line with the feedability factor, as discussed on page 90. The General Purpose Aircraft Grease appears to feed by controlled liberation of an oily phase, as it is of medium consistency.

Phase II of the Laboratory Panel work will be to study a new radially loaded tester (Model SKP-1721-1) designed by the Sikorsky Aircraft Division of the United Aircraft Corporation. The tester pictured in Figure 11, page 93, will accommodate

*Coordinating Lubricant and Equipment Research Committee of the Coordinating Research Council, Inc.

TABLE VI*

Fretting Corrosion Resistance of Various Materials Under Dry Conditions

Low	Medium	High
Steel on steel	Cadmium on steel	Lead on steel
Nickel on steel	Zinc on steel	Silver plate on steel
Aluminum on steel	Copper alloy on steel	Silver plate on aluminum plate
Aluminum-silicon alloy on steel	Zinc on aluminum	Parkolubrited steel on steel
Antimony plate on steel	Copper plate on aluminum	
Tin on steel	Nickel plate on aluminum	
Aluminum on aluminum	Silver plate on aluminum	
Zinc-plated steel on aluminum	Iron plate on aluminum	
Iron-plated steel on aluminum		

*Sakmann and Rightmire NACA Technical Note 1492, June (1948).

tapered roller, needle or ball bearings by means of suitable adapters.

MITIGATION OF FRETTING AND FRETTING CORROSION

It should be apparent by now that a case study must be made of the variables and the environment in any particular instance before a satisfactory solution can be reached. In some cases this might call for a change in design to obtain elimination of fretting. Where such is not feasible, fretting may be helped, not cured, by certain practices, some of which are listed on the opposite page.

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*NACA Technical Note 3029 summarizes an intensive investigation of fretting corrosion carried out during a period of several years and as such is a valuable compilation. For further reference, three papers have been published elsewhere, basis this work. The first is Reference 6 above which described the equipment design and operating procedures. Two other papers, published in the Journal of Applied Mechanics, Vol. 21, No. 4 (December 1954) are "Mechanism of Fretting Corrosion," by H. H. Uhlig (p. 401), and "Fretting Corrosion of Mild Steel in Air and in Nitrogen," by I. M. Feng and H. H. Uhlig (p. 395).

Printed in U. S. A. by
Salley & Collins, Inc.
305 East 45th Street
New York 17, N. Y.

Some Suggestions

for

Relieving Fretting Corrosion

1. Submerge or flood bearing with lubricant of maximum feedability.

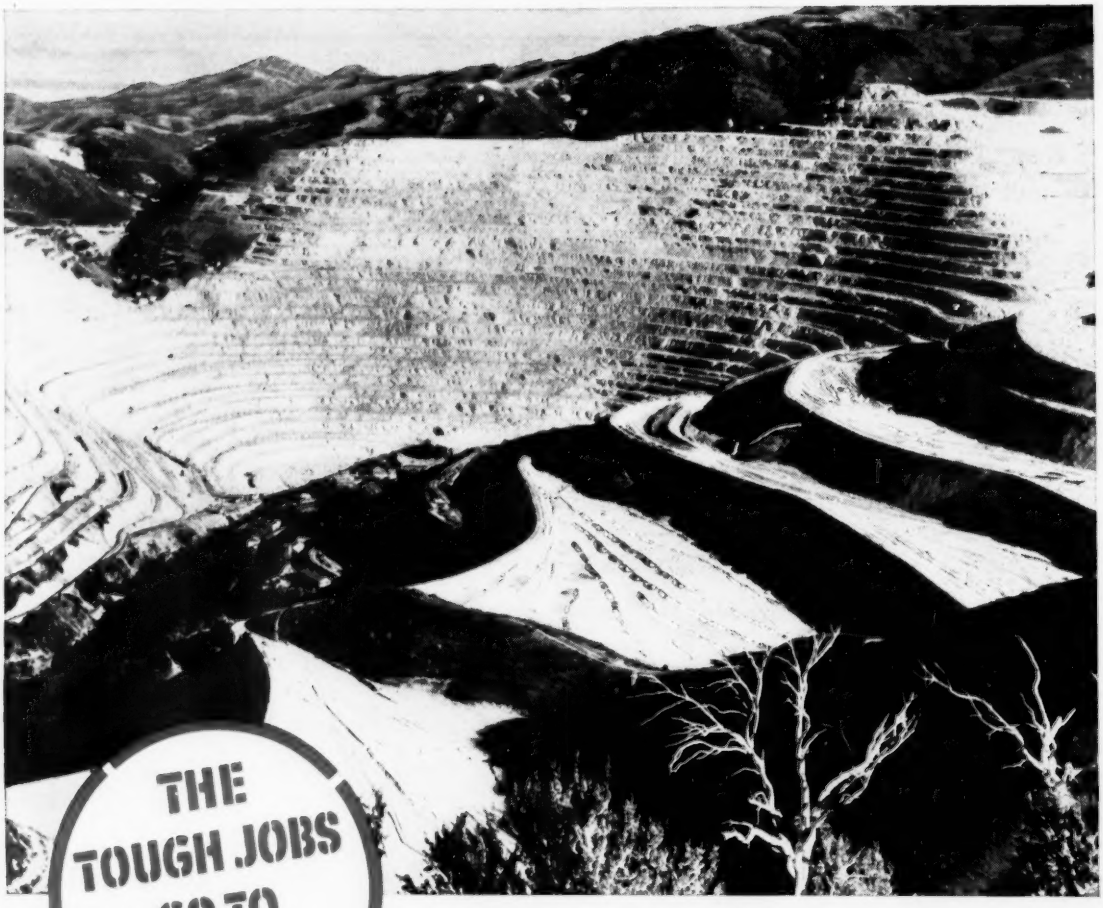
2. Relubricate bearing frequently to flush out accumulated iron oxide debris.

3. Modify the surfaces; vapor blasting or baked-on MoS_2/resin, Teflon, or sacrificial coatings of lead, chromium, indium, or copper may be helpful.

4. Harden one steel surface by metalizing; it has been stated that building up one surface with 1.2 per cent carbon steel and cold rolling is effective for press fits.

5. Coat surfaces with rubber or rubber cement — while not usually feasible, this procedure is effective as the rubber damps vibration within itself, i.e. takes up the slip internally.

6. Increase amplitude of oscillation in the case of antifriction bearings — this was effective in overcoming the fretting corrosion of wheel bearings of automobiles shipped in box cars (accomplished by loosening tiedown rods and softening tires); by so doing, fresh grease was dragged into the rubbing areas.



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